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Effects of Operating Parameters on the Beam Species of DIII–D Neutral Beam Ion Sources

R. Hong and H.K. Chiu

General Atomics, P.O. Box 85608, San Diego, California 92186-5608

Abstract—The DIII–D fusion science research facility employs positive-ion based neutral beam ion sources for plasma heating and current drive experiments. Ion species produced inside the arc chamber of an ion source determine the composition of the neutral beams injected into the plasma and in turn affect the energy deposition along the cross section of the plasma. Arc chamber design and operation schemes are the predominant factors in the ion species mix when an arc discharge is produced inside the arc chamber. When deuterium gas is used for arc discharge three deuterium ion species (atomic D_1^+ and molecular D_2^+ and D_3^+) are produced in the arc chamber of the DIII–D neutral beam ion source. Atomic ion D_1^+ has the highest percentage of the three species, normally about 80% of ions produced. Measurements have shown that both D_1^+ and D_2^+ decrease slightly with lower arc power discharges. However, D_3^+ increases at a higher rate when arc power is reduced. Changing the fraction of the ion species can be beneficial to or meet the needs of some specific plasma experiments. An attempt to manipulate the ion species mix by changing the operating parameters of the arc chamber/ion source has been performed. These operating parameters include filament temperature, arc power, beam energy, and gas flow. Interesting results were obtained which show that arc power is the dominant factor for controlling the species mix. We were not able to significantly change the ion species mix by varying the operating parameters within the operation window when the ion source is operated at constant beam energy. However, the D_3^+ fraction increased by a factor of three when the ion source was operated at a much lower arc power (for 50 keV beam energy operation) than the higher arc power required for ion source operation with beam energy between 75 to 80 keV.

I. Introduction

Fig. 1 shows the schematic of the DIII–D neutral beam ion source. The ion source consists of an arc chamber and an accelerator. The plasma inside the arc chamber is produced by the arc discharge in the emission-limited regime. The accelerator extracts and accelerates ions from the arc chamber. The high voltage applied to the source grid of the accelerator is the energy the ions (of all species) will gain and is normally called the beam energy. However, deuterium neutral beams injected into the DIII–D plasmas consist of neutralized ions with three different energies (called full-, half-, and third-energy), due to neutralization and dissociation of the molecular ions. The penetration (and thus the energy deposition) of these neutral beams with three different energies into the plasma is of interest to the physics experiments. The capability of varying the species mix will add flexibility for some specific experiments. The interest is in achieving this capability by changing the operating parameters. These operating parameters include filament temperature, arc power, beam energy and gas flow rate. However, only one parameter is varied for each set of tests to examine its effect on the species mix. Since Doppler shifted D_α signals of the neutralized ions were used to measure the species mix, ion beams need to be extracted from the arc chamber and accelerated through the accelerator, thus operating parameters have to stay within their operational windows. This imposed a limitation on the range of parameter scans allowed in our tests.

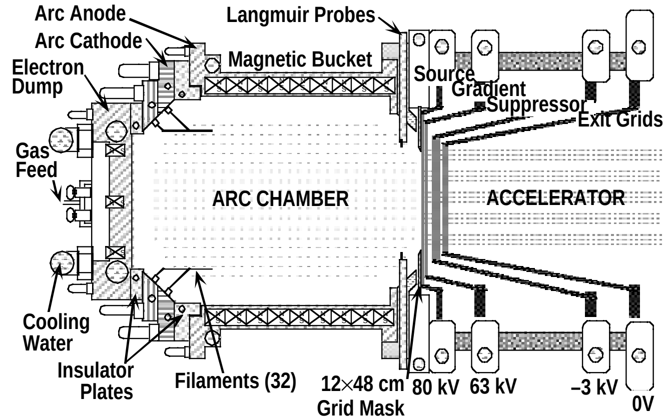

Fig. 1. Schematic of DIII–D neutral beam ion source.

II. Operating Parameters and Test Procedures

A. Operating Parameters

One ion source was operated with 1 s pulse length deuterium beams for this experiment. Ranges of the ion source operating parameters are:

Beam energy: 50 to 80 keV
Arc power: 40 to 85 KW
Voltage applied to the filaments: 6.80 to 7.05 V
Gas flow into the arc chamber: 13 to 20 Torr·ℓ/s

B. Test Procedures

Ion species mix was measured for each of the following ion source operating parameter scans:

1. Vary the voltage applied to the filaments while keeping all other operating parameters unchanged.
2. Vary the arc power (by changing the Langmuir probe signals, which are used to increase or decrease the ion density of the arc discharge inside the arc chamber) while keeping all other operating parameters unchanged.
3. Vary the beam energy and the corresponding arc power for proper beam extraction within the operating window while keeping other parameters unchanged.

4. Vary the amount of deuterium neutral gas flowing into the arc chamber for the discharge while keeping all other operating parameters unchanged.

III. COMPARISON OF ION SPECIES MIX

A. Effects of Filament Temperature on the Species Mix

Fig. 2 shows the plot of species mix, arc power and arc voltage as functions of the voltage applied to the filaments (called filament voltage) when gas flow, beam energy, and Langmuir probe signal were all held constant. The number of atomic ions increases slightly when more thermal electrons are emitted from the filaments. However, the effect is fairly small within the range of the filament voltage scan from 6.80 to 7.05 V. Since ion source operation and beam optics (beam current and beam divergence) are very sensitive to the filament temperature [1], [2], it limits the filament voltage range for stable ion source operation. When filaments become too cold or too hot, poor beam optics and large beam divergence will result in beam termination to protect the ion source and beamline. The arc discharge will also switch from emission-limited to space charge-limited mode and become unstable when filaments are too hot. A scan over a wider filament temperature range to observe its effects on ion species is thus very difficult to do. It should be noted that the arc power was kept constant throughout the filament voltage scan and the arc voltage decreased when more thermal electrons were produced from the filaments. It is interesting to note that a higher arc voltage (from which thermal electrons gain energy and ionize the neutral gas in the arc discharge process) produces fewer atomic ions, but more molecular ions.

B. Effects of Arc Power and Beam Energy on the Species Mix

Within the ion source operation window, arc power can be varied with fixed beam energy and filament voltage. The arc power is controlled by the values set for the Langmuir probe signal. Fig. 3 shows that the fraction of atomic ions (D_1^+ ions) increases slightly with arc power. The range of arc power is limited by beam optics suitable for ion source operation. To obtain a much wider arc power scan, the beam energy needs to be adjusted to match the arc power, a process called perveance matching. Fig. 4 shows the beam energy and species mix as functions of the arc power. The fraction of the molecular ions (D_3^+ ions) increases significantly (about 3 times) when the arc power decreases from 85 kW to 40 kW (beam energy decreases from 80 keV to 50 keV) while D_1^+ and D_2^+ ion fractions decrease linearly with arc power.

The most important and useful neutral beam data for plasma physics experiments are the injected neutral beam power and the fraction of power of individual neutral beam species (full-, half-, and third-energy neutrals). The injected beam power has been determined from the beam energy, beam current, neutralization efficiency, beam transmission efficiency, and re-ionization loss. Using data shown in Fig. 4, and the neutralization efficiency of each ion species, the fractions of neutral beams of each of the three different energies are obtained and shown in Fig. 5.

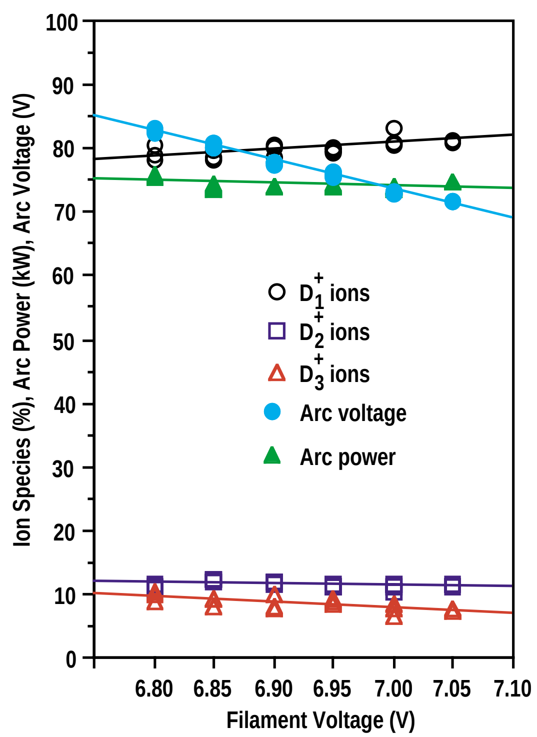

Fig. 2. The Effect of filament temperature on the species mix is small.

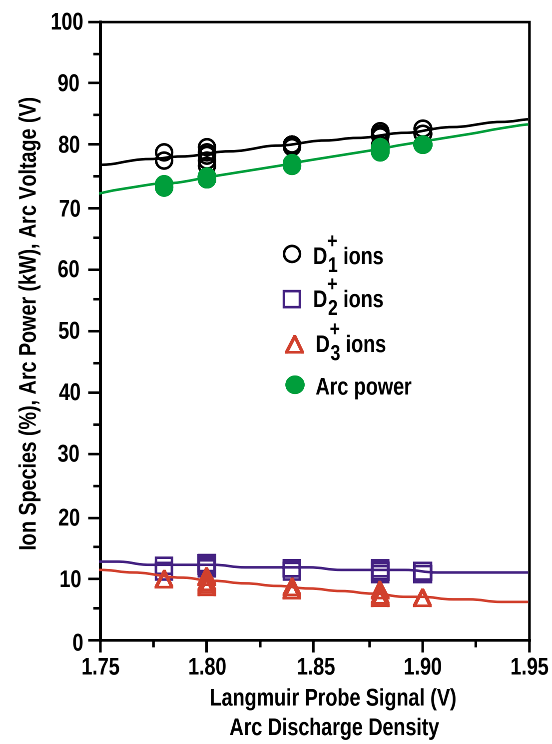

Fig. 3. Species mix within the operation window for a specific beam energy.

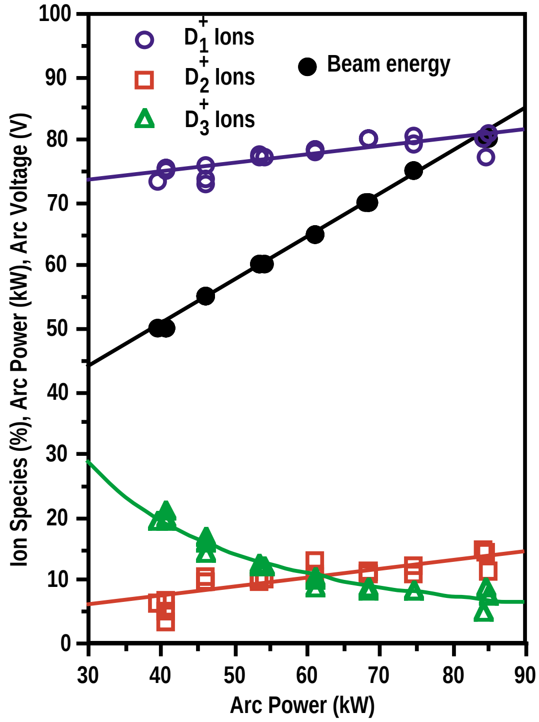

Fig. 4. Fraction of D_3^+ ions increases significantly when the ion source is operated at lower arc power (or lower beam energy).

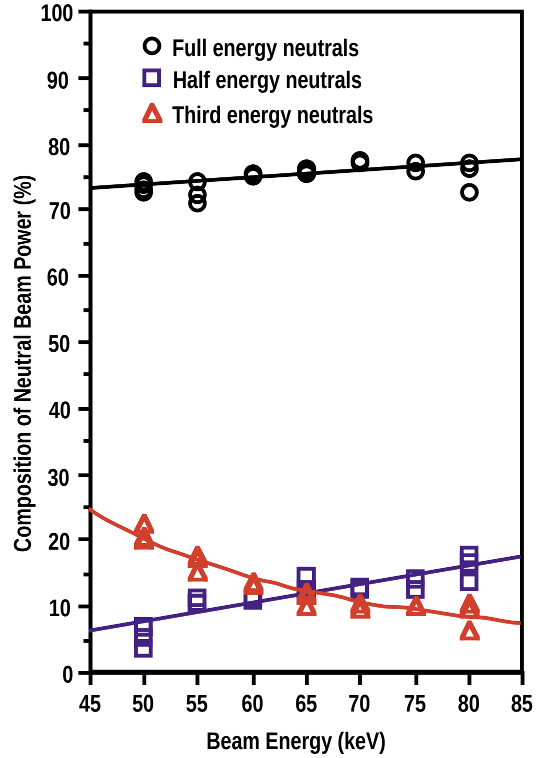

Fig. 5. Composition of neutral beams as function of beam energy.

C. Effects of Gas Flow into the Arc Chamber on the Species Mix

With all other operating parameters unchanged the amount of neutral gas flowing into the arc chamber for arc discharge was varied from 13 to 20 Torr·ℓ/s, and the species mix was measured. Fig. 6 shows that the fraction of the atomic ions, D_1^+, stays fairly constant, however, the fractions of molecular ions, D_2^+ and D_3^+, decrease and increase linearly, respectively, with the amount of gas flowing into the arc chamber. It should be noted, as shown in Fig. 7, that both arc power and arc voltage to sustain a constant ion density decrease as more neutral gas flows into the arc chamber. Lower arc voltage produces fewer D_3^+ ions (Fig. 2), but lower arc power produces more D_3^+ ions (Fig. 4). In this gas flow test we have these two effects (Fig. 7). The resultant effect is that more D_3^+ ions are produced when more gas flows into the arc chamber, indicating that arc power has a stronger effect on ion species than the arc voltage. This result can also be applied to explain the parametric effects on the D_1^+ and D_2^+ ions production.

IV. Conclusions

We have performed tests of varying operating parameters of the DIII–D neutral beam ion source to study the changing of the beam species mix. The results show that when the ion source is operated at a specific beam energy, changing ion source operating parameters cannot alter the beam species mix significantly. However, the molecular ion fraction, D_3^+, increases sharply when the ion source is operated at lower arc power level (equivalent to lower beam energy), and the full and half energy beam species decrease linearly with arc power. We conclude that beam species mix is only a weak function of ion source operating parameters.

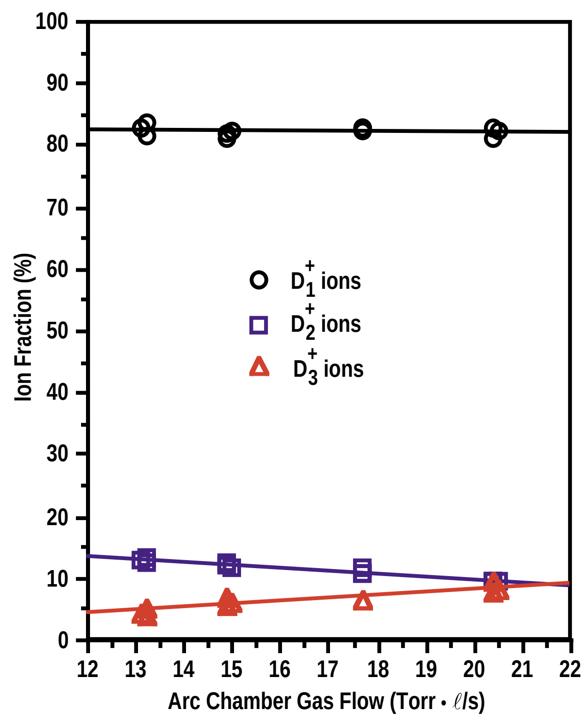

Fig. 6. Amount of neutral gas inside the arc chamber has some effect on the production of D2 and D3 ions.

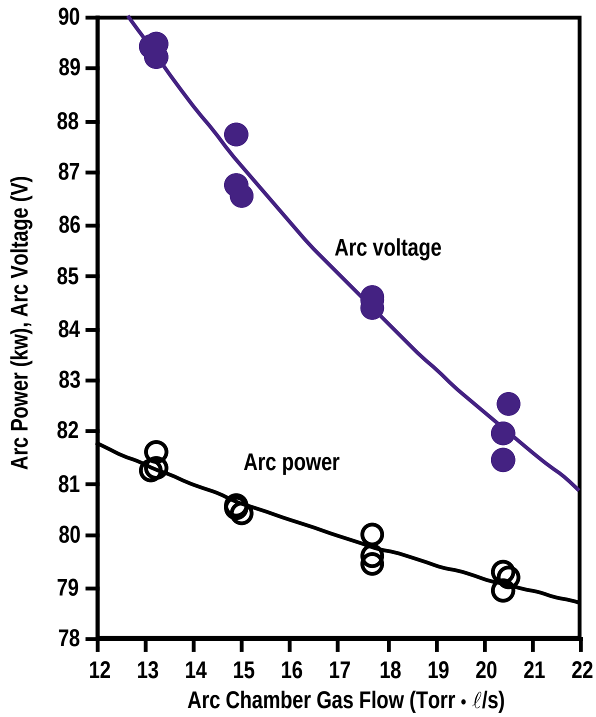

Fig. 7. Lower arc voltage and lower arc power are required to sustain the arc discharge with larger gas flows into the arc chamber.

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